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ORIGINAL ARTICLE

Frontal Knee Alignment

Three-dimensional Marker Positions and Clinical Assessment

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Abstract We assessed the validity of the hip-knee-ankle angle measured statically during three-dimensional (3-D) gait analysis and the tibial angle using an inclinometer compared with the mechanical axis on radiographs. Eleven individuals (20 knees) with radiographic knee osteoarthritis (OA) participated in this study. We determined the following: the lower-limb mechanical axis using weight-bearing long-leg radiographs; hip-knee-ankle angle using the techniques of 3-D gait analysis in a static standing position; and tibial alignment using an inclinometer. The mean mechanical axis (± standard deviation) for this cohort was 0.7° ± 7.2° (range, −13°−16°). The tibial alignment and hip-knee-ankle angle correlated with the mechanical axis but the correlation between the mechanical axis and the hip-knee-ankle angle was stronger. Our data suggest the inclinometer and 3-D gait analysis are valid ways to estimate mechanical alignment of the knee.

Each author certifies that he or she has no commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.
Each author certifies that his or her institution has approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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Introduction

The influence of knee loading on the severity [19], progression [16], and treatment outcome [21] of OA has been recognized. An understanding of the mechanical factors influencing loading on the knee is crucial for better insight in the disease process and development of new prevention and treatment strategies. One of the major contributors to the mechanical loading of the knee is the static alignment of the lower limb [11]. Among the population with OA, varus alignment of the knee is widely spread. Previous investigations suggest greater than 50% of patients with OA have varus-aligned legs [7, 23]. Patients with more severe knee OA have a 6° greater varus mechanical alignment compared with patients with less severe knee OA [18]. Sharma et al. [23] reported increased varus alignment increased the risk of medial progression by fourfold. Knee malalignment is also a likely mediator of the OA-obesity relationship [22], because increased loading of malaligned joints would tend to accentuate wear, which increases the malalignment and consequently increases abnormal loading on the medial site of the tibiofemoral joint [7].

Orthopaedic surgeons have been using high tibial osteotomy successfully for many years to correct varus alignment of the knee. The goal of the corrective osteotomy is to transfer load bearing from the pathologic to the normal compartment of the knee. This corrective surgery can improve knee function and cartilage regeneration [14, 15, 20]. However, recurrence of varus deformity 5 to 10 years after the surgery has been linked to the knee frontal plane valgus angle after surgery being either too small or too great [6, 8, 12, 14, 15]. Coventry et al. [6] reported better outcomes 3 to 14 years postsurgery when knees were corrected to more than 8° valgus. Knees aligned between 7° and 10° valgus had better conservation of the angulations 11.5 years after the surgery [8]. Koshino et al. [15] observed no loss of angulation after more than 15 years and good preservation of the knee and function scores in knees with a valgus angulation greater than 10°. Therefore, successful outcome of the surgery depends on an accurate estimate of alignment of the limb.

Despite the importance of limb alignment in the progression and treatment of OA, assessment of alignment is still problematic. The gold standard is weightbearing, long-leg radiographs, which allow the mechanical and anatomic axes of the lower limb to be determined. These radiographs are relatively costly and sometimes not readily available, and also expose the pelvis to ionizing radiation. Hinman et al. [9] suggested clinical measurements using an inclinometer, a plumb line, a caliper, or a goniometer are reasonable without risk for patients or extra costs. In particular, use of an inclinometer and caliper seemed to provide an accurate indication of the mechanical axis compared with the radiographic measures.

Although knee alignment is a composite of the tibial and femoral alignment, the inclinometer only measures one part of the alignment. Femoral malalignment cannot be detected using the inclinometer. Gait analysis typically determines the 3-D joint moments and movements and has been used to estimate disease risk and progression in patients with OA [4, 18]. During gait analysis, a static weightbearing standing position can be recorded as an anatomic reference position to calculate the joint coordinate system and static alignment of the knee, the hip-knee-ankle (HKA) angle.

Our aims were to determine (1) the reproducibility of two of these procedures (hip-knee-ankle angle using 3-D gait analysis in a static standing position and tibial alignment using an inclinometer) and (2) the correlation between these measures and the mechanical axis on radiographs, which is considered the gold standard for determining knee alignment.

Materials and Methods

We prospectively enrolled 11 patients (20 knees) with radiographic and symptomatic OA of the knee who were participating in an ongoing longitudinal study evaluating the effects of tibial osteotomy on gait characteristics. Patients were eligible if they had radiographic and clinical OA according to the American College of Rheumatology [1]. The study group (eight men and three women) had a mean age of 55 ± 6.6 years (standard deviation [SD]) and a mean body mass index of 30.3 ± 3.6 kg/m^2. This study was approved by The University of Sydney Human Ethics Committee and written informed consent was obtained from each patient.

Standard weightbearing posteroanterior long-leg radiographs of both legs were obtained for each subject according to the protocol of Moreland et al. [17]. Patients stood barefoot with the knees in full extension and were positioned with the tibial tuberosity facing the xray beam. Femoral and tibial mechanical axes and alignment of the knee were determined using a manual method. Each angle was measured by one of the authors (BV) with a radiographic goniometer after landmarks were identified and marked. The mechanical axis was defined as the angle formed by a line from the center of the femoral head to the intercondylar notch and that of the tibia by a line from the center of the tibial spines to the center of the talus (Fig. 1). The center of the femoral head was determined using a template with concentric circles. As recommended by Cooke et al. [5], mechanical axis angle was expressed as

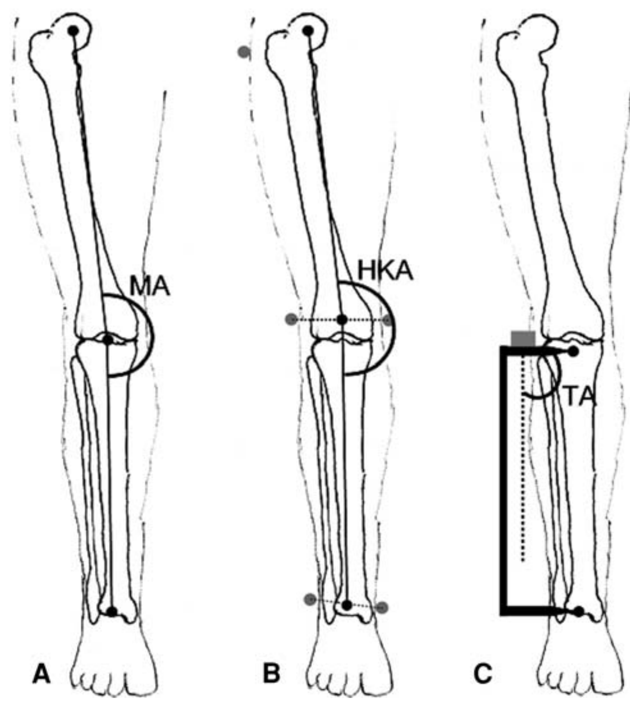

Fig. 1A–C The drawings show the calculation of the three alignment axes. (**A**) The mechanical axis was defined as the angle formed by a line from the center of the femoral head (black point) to the center of the tibial spines (black point) and a line from the center of the tibial spines to the center of the talus (black point). (**B**) The static hip-knee-ankle angle during gait analysis was determined as the angle between the long axis of the shank and the thigh; the axis of the shank was determined from a line from the mid-point of the femoral condyles and the mid-point of the malleoli; the axis of the femur was determined from a line from the center of the hip to the mid-point of the femoral condyles. The gray points are the external markers and the black dots are the calculated hip, knee, and ankle centers. (**C**) The tibia angle was defined as the angle formed by a line from the tibial tuberosity (black point) and the middle of the talar head (black point) and a vertical line (dotted line) determined by an inclinometer (gray box).

deviation from 180° with a negative value for varus and positive values for valgus alignment.

For measurements with the inclinometer, participants were asked to stand with both feet on a standardized foot map (two lines to align the long axis of the foot and the border of the heel) that aligned the second metatarsal and the middle of the heel with their feet approximately 29 cm apart and their weight distributed equally over both feet. To assess orientation of the tibia, the tibial tuberosity and the middle of the talar head were identified. A gravity inclinometer was mounted to a set of calipers and the arms of the calipers were positioned on the two landmarks (Fig. 1). The angle of the tibia was measured with respect to the vertical. Varus was defined as negative values and valgus as positive values.

To measure the HKA, we placed retroreflective spherical markers on prominent anatomic landmarks to indicate 12 body segments (forefoot, midfoot, rearfoot, shank, thigh, pelvis, and thorax) and six lower body joint centers (ankles, knees, and hips). The 3-D position of each marker was calculated using 10 cameras (Eagle 8 mm; Motion Analysis Corp, Santa Rosa, CA) recording at 100 Hz and a motion analysis system (EvaRT4.6; Motion Analysis Corp). Participants were asked to stand with both feet parallel on the foot map and with their weight distributed over the two feet. This position was recorded during 5 seconds. Lower limb joint center locations were determined using relative marker positions. The midpoint between the medial and lateral malleoli markers indicated the ankle center. The midpoint between the medial and lateral femoral condyles indicated the knee center. The hip center was determined using the technique outlined by Bell et al. [2]. A 3-D joint coordinate system was calculated by a software package (KinTrak 6.2; Motion Analysis Corp). The long axis of the shank was defined as the vector from the knee center to the ankle center and the long axis of the thigh was the vector from the hip center to the knee center. The medial/lateral axis of the shank was the vector from the medial to lateral condyle of the femur. The anteroposterior axis is the cross product between the medial/lateral axis and the long axis of the shank. The HKA knee was the angle between the long axis of the thigh and the shank around the anteroposterior axis (Fig. 1).

The reproducibility of the HKA angle and the tibial angle was determined by measuring three healthy subjects on three separate occasions. The mean and SD of the three replicated measures were determined. The root mean square (RMS) SD was used to determine the average SD and percentage coefficient of variation of the quantitative computations in all three subjects. Repeated measures of the tibial angle and the HKA angle on three separate days resulted in RMS SDs of 0.68° and 0.70°, respectively.

Data were checked for normal distribution using histograms. If normally distributed, we correlated the mechanical alignment and HKA angle and the mechanical alignment and tibial angle using Pearson's correlation coefficients. Nonnormally distributed data were logged and checked for normal distribution. If the logged data were not normally distributed, nonparametric tests were used. Data were analyzed using SPSS® Version 14.0 (SPSS Inc., Chicago, IL).

Results

Eight of 20 knees (40%) had valgus alignment, seven knees (35%) had varus alignment, and five knees (25%) had neutral alignment. The mean mechanical axis for our cohort was 0.7° ± 7.2° (range, −36°−13°) (Table 1). The mean HKA angle measured with the static 3-D gait analysis technique was 4.6° ± 6.5° and the tibial angle measured using an inclinometer was 0.06° ± 3.6° (Table 1).

The tibial angle (inclinometer) and HKA angle (gait analysis) correlated with the mechanical axis (radiograph) ($r = 0.831$, $p < 0.001$ and $r = 0.934$, $p < 0.001$, respectively). The HKA angle accounted for 87% of the variance in the mechanical axis. The linear regression analysis

Table 1. Alignment characteristics of the cohort (n = 20 knees)

Alignment characteristic (method)	Value (degrees)
Mechanical axis (weightbearing long-leg radiographs)	0.7 ± 7.3
Hip-knee-ankle angle (3-D gait analysis)	4.6 ± 6.5
Tibial angle (inclinometer)	0.06 ± 3.6

Values are expressed as mean ± standard deviation.

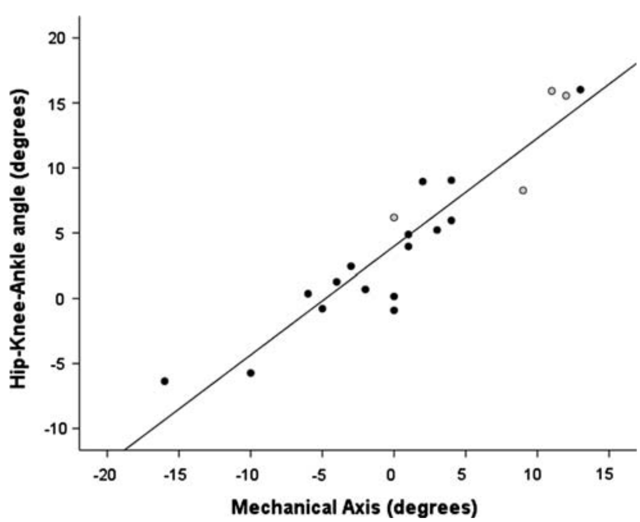

Fig. 2 A scatterplot depicts a relationship between the mechanical axis and the hip-knee-ankle angle (n = 20 knees). The gray points are the cases surgically realigned.

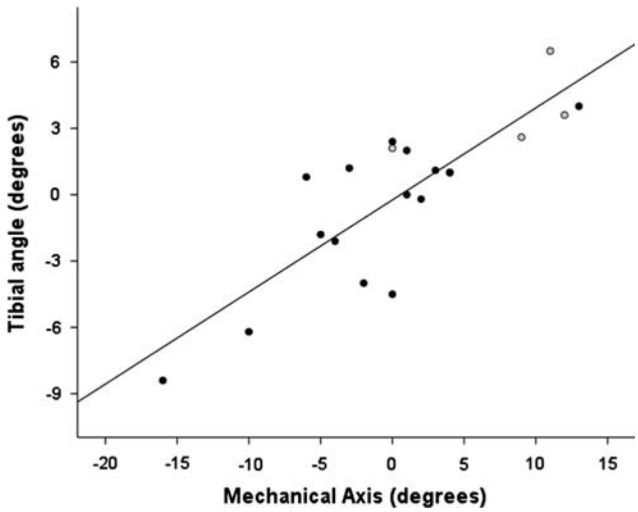

Fig. 3 A scatterplot depicts a relationship between the mechanical axis and the tibial angle (n = 20 knees). The gray points are the cases surgically realigned.

defined this relationship as: mechanical axis = −4.05 + 1.05 (HKA angle) (Fig. 2). The standard error of the estimate was 2.4. The tibial angle accounted for 69% of the variability in the mechanical axis. The linear regression analysis defined the relationship between the tibial angle and the mechanical axis as: mechanical axis = 0.6 + 1.66 (tibial angle) (Fig. 3). The standard error of the estimate was 2.1. The tibial angle (inclinometer) and HKA angle (biomechanical analysis) also were correlated ($r = 0.837$, $p < 0.001$).

Discussion

The mechanical axis measured using weightbearing radiographs of the lower limbs is regarded as the gold standard to assess alignment of the lower limb. Our two aims were to determine the reproducibility of the tibial angle as measured by an inclinometer and the HKA angle as measured by 3-D gait analysis and to determine the correlation between these measures and the mechanical axis on radiographs.

One of the limitations of this study is the small sample size. This sample size limits the investigation of the effect of numerous clinical variables such as obesity and joint range of motion restriction. Our conclusions are valid for our study population; however, additional research is needed to investigate the validity of this measurement in a broader population. We used the method of Moreland et al. [17] to define the mechanical axis on weightbearing radiographs. This method is based on one knee center point, which reduces the possibility for a comprehensive analysis [5]. Future studies should consider using the method of Cooke et al. [5], which would allow identifying the contribution of each limb to knee alignment. Another limitation of our study is the method used to estimate the hip center. Kirkwood et al. [13] compared different predictive models and reported the method of Bell et al. [2] places the hip center more lateral, which would underestimate varus alignment. The use of other methods, including a functional method [3], could improve the accuracy of the HKA angle, but additional investigations will have to determine the validity of other models. Siu et al. [24] described the use of a standardized procedure to control foot and hip position results in better reproducible results. We controlled the position of the foot during the inclinometer and the biomechanical analysis; however, we used no such control during the radiographic filming.

We observed a correlation between the mechanical axis measured by weightbearing radiographs of the lower limbs and the HKA and tibial angles. The relationship between mechanical axis and HKA angle was slightly stronger than the relationship between mechanical axis and tibial angle. Our findings for the tibial angle were similar to the results of Hinman et al. [9]. They reported a correlation between the inclinometer method and the mechanical axis in a cohort of 40 patients with symptomatic medial knee OA. The average mechanical axis in their cohort was 5.8° varus. Our average mechanical axis was 0.7° valgus. This is mainly because valgus, varus, and neutral alignment were almost equally represented in our cohort. Our inclusion criteria did not specify the OA location (lateral or medial); therefore, our study included four knees with lateral OA and four knees with medial OA that were corrected to a valgus alignment previously using high tibial osteotomy.

The slope of the linear regression indicates, for each 1° in mechanical alignment, there will be a change of 1.05° for the HKA angle and 1.7° for tibial alignment. This relation seems reasonable for HKA angle; however, the tibial alignment will exaggerate the alignment and cause discrepancies between the mechanical axis and tibial angle, especially in the larger varus-valgus angles. The standard error of estimates shows the error for estimating the mechanical axis for both measurements is approximately 2°. Previous studies have reported a range of optimal angulation between 8° and 11° valgus [6, 8, 15]. This angulation postsurgery relates to long-term conservation of the angulation and good knee and function scores. The error of the predicted angle is within the degree of accuracy required to apply surgical correction.

Our data suggest the HKA angle measured using 3-D gait analysis is a reproducible and accurate estimate of the mechanical axis. There are several advantages of using 3-D biomechanical analysis instead of weightbearing radiographs. First, biomechanical analysis does not use any radiation and is noninvasive. Also, because it is a 3-D measurement using a local joint coordinate system, there is no need to precisely align the subject and accuracy of the method will not be influenced by positioning of the subject. The latter causes problems in long-leg radiographs [10]. Several studies [10, 24] have shown subject positioning, especially foot rotation, is an important factor when measuring the mechanical axis from long-leg radiographs. Although the 3-D analysis will be able to accurately reflect the HKA, the inability of patients to fully extend their knees will influence this HKA angle, such as with an increase in flexion, the knee will abduct more. The use of 3-D biomechanical analysis, however, has disadvantages, in particular, its lack of availability, long assessment time, and costs. A 3-D gait laboratory is not available for everyone, and the setup and calibration of the cameras and placement of the markers can take as much as 30 minutes. This would come at a cost because a laboratory technician must be paid for that time and there are other acquisition and maintenance costs. The patients' time would be approximately 30 minutes including patients' changing clothes, marker placement, and measurement of the neutral position. Markers must be placed accurately to get a reliable measurement of the HKA angle. Biomechanical analysis measures the position of the bones in an indirect way, so careful placement of the markers is needed. To reduce the error of marker placement, the same experienced assistant was used throughout our study. The high reproducibility of the HKA angle shows marker placement can be performed in a reliable manner. As a result of time, effort, and cost, a 3-D biomechanical analysis for the sole purpose of measuring alignment is not viable. However, when such an analysis is planned for a patient, measurement of this neutral position in addition to the gait could replace the long-leg radiographs.

Our data also suggest the tibial angle measured with an inclinometer is a valid alternative to the mechanical axis. The method is widely available, does not involve any radiation, and is inexpensive. The technique is again an indirect estimate of bony landmarks, which could cause error. Positioning of the feet and control of the base of support are important in this method, because standing with a wider base of support will place the tibia in a more valgus position. Therefore, use of the foot map is essential to this method. One of the limitations of the tibial angle is it only measures alignment of one bone, whereas knee alignment is the composite of tibial and femoral alignment. Although the tibial angle measures varus or valgus from the horizontal, it does not provide information regarding the origin of the deformity. The use of the tibial tubercle is another limitation of this method. Yoshioka et al. [25] reported the location of this anatomic reference point is very variable.

The inclinometer and gait anatomic static trial are reproducible and accurate measurement methods to estimate the mechanical alignment of the knee.

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